

# PREGALACTIC LIBEB PRODUCTION BY SUPERNOVA COSMIC RAYS

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## ABSTRACT

I calculate the evolution of Be and B abundances produced by cosmic rays generated by massive stars in the pregalactic phase of the universe. The inputs for calculation, i.e. the star formation rate and the nuclear abundances of cosmic rays, which I assume to be the same as those of the ISM, are taken from the results of a detailed cosmic chemical evolution model with its parameters best fitted from several items of observational information including an early reionization of the IGM by  $z \sim 15$ . I found that when the  ${}^6\text{Li}$  plateau abundance observed in metal-poor halo stars originated in the pregalactic cosmological cosmic ray nucleosynthesis, Be and B simultaneously produced with  ${}^6\text{Li}$  amount to the lowest levels ever detected in metal-poor halo stars. It is desirable to observe Be and B abundances in metal-poor halo stars with  $[\text{Fe}/\text{H}] \leq -3$  in order to elucidate the possibility of early  ${}^6\text{LiBeB}$  production by pregalactic supernova cosmic ray nucleosynthesis.

*Subject headings:* cosmic rays — cosmology: theory — nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: Population II — supernovae: general

## 1. INTRODUCTION

The lithium abundances observed in metal-poor halo stars (MPHSs) show a plateau as a function of metallicity (Spite & Spite 1982; Ryan et al. 2000; Meléndez & Ramírez 2004; Asplund et al. 2006; Bonifacio et al. 2007; Shi et al. 2007) at  ${}^7\text{Li}/\text{H} = 1 - 2 \times 10^{-10}$ . The prediction by the standard big bang nucleosynthesis (BBN) model of  ${}^7\text{Li}$  abundance which is the main lithium isotope observed in MPHSs, however, indicates a factor of 2 – 4 larger value, when the baryon-to-photon ratio deduced from parameter fits to the temperature fluctuations of cosmic microwave background (CMB) radiation measured with Wilkinson Microwave Anisotropy Probe (WMAP) (Spergel et al. 2003, 2007) is used. For example, Coc et al. (2004) derived  ${}^7\text{Li}/\text{H} = (4.15^{+0.49}_{-0.45}) \times 10^{-10}$  with the baryon-to-photon ratio  $\eta = (6.14 \pm 0.25) \times 10^{-10}$ . This discrepancy between the observations and the BBN+CMB prediction of  ${}^7\text{Li}$  abundance is a problem, which indicates some destruction process of  ${}^7\text{Li}$ . Recently, a complex but consistent theory is suggested by Piau et al. (2006). In their theory, an extremely high efficiency of engulfment of baryons in a first generation of stars results in a half or one third of destructions of D and Li isotopes. Population II (Pop II) stars are made of a mixture of ejecta of supernovae (SNe) of the first stars and unprocessed material of the primordial composition, and experience a depletion of lithium isotopes in their atmospheres, which are observed. There are two important conditions. The ejecta of SNe of the first stars needs to mix with the pure BBN-composition matter at  $2.5 \leq [\text{Fe}/\text{H}]^2$  in order to form the lithium plateau. An infall of the intergalactic medium (IGM) needs to proceed after the formation of Pop II stars in order to be consistent with observations of deuterium

abundance.

Recent spectroscopic observations of MPHSs also provide abundances of  ${}^6\text{Li}$  isotope. They indicate a likely primordial plateau abundance, similar to the well known  ${}^7\text{Li}$  plateau, of  ${}^6\text{Li}/\text{H} = 6 \times 10^{-12}$ , which is about 1000 times as large as the BBN prediction. Since the standard Galactic cosmic ray (CR) nucleosynthesis models predict negligible amounts of  ${}^6\text{Li}$  abundance with respect to the observed plateau level at  $[\text{Fe}/\text{H}] < -2$  (e.g. Prantzos 2006), this plateau causes another problem, which indicates some production process of  ${}^6\text{Li}$ .

Several candidates for early  ${}^6\text{Li}$  production mechanisms have been suggested. The non-thermal nuclear reactions triggered by the decay of long-lived particles is one possibility of the non-standard process (Jedamzik 2000, 2004a,b, 2006; Kawasaki et al. 2005; Kusakabe et al. 2006; Cumberbatch et al. 2007). Pospelov (2006) suggested the exotic nuclear reaction of  ${}^4\text{He}_X(d, X^-){}^6\text{Li}$  to make abundant  ${}^6\text{Li}$ , where  $X^-$  is a negatively charged massive particle assumed to decay in the early universe, and  ${}^4\text{He}_X$  is the state that has  ${}^4\text{He}$  bound to  $X^-$ . Suzuki & Inoue (2002) suggested an  $\alpha + \alpha$  fusion reaction with  $\alpha$  particles accelerated by hierarchical structure formation shocks, thought to have been operative at the Galaxy formation epoch.

As a possibility, Rollinde et al. (2005) have calculated the  ${}^6\text{Li}$  production by an initial burst of cosmological cosmic rays (CCRs) to show that this process through  $\alpha + \alpha$  fusion can account for the  ${}^6\text{Li}$  plateau without overproduction of  ${}^7\text{Li}$ . Rollinde et al. (2006) applied the CCR nucleosynthesis to a well grounded detailed model. They derived the total CCR energy as a function of redshift from a star formation rates (SFRs) in models of cosmic chemical evolution of Daigne et al. (2006), which are made to reproduce the observed cosmic SFR, SN II rate, the present fraction of baryons in structures, that in stars, the evolution of the metal content in the interstellar medium (ISM) and IGM, and early reionization

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<sup>2</sup>  $[A/H] = \log(A/H) - \log(A/H)_\odot$

of the IGM. As a result they found that the pregalactic production of the  ${}^6\text{Li}$  in the IGM via Population III (Pop III) stars can account for the  ${}^6\text{Li}$  plateau without overproduction of  ${}^7\text{Li}$ .

The CR nucleosynthesis also produces Be and B by spallation reactions between CNO nuclei and  $p$  and  $\alpha$  particles. If this CCR nucleosynthesis scenario of  ${}^6\text{Li}$  production leads to overproduction of Be and B nuclides against observations in metal-poor stars, it cannot be achieved in the real universe. This study is devoted to checking if the CCR nucleosynthesis as a mechanism of  ${}^6\text{Li}$  production is consistent with observations of Be and B in metal-poor stars, and finding constraints on conditions of the CCR nucleosynthesis.

Abundances of Be and B are observed in MPHSS. A trend of  ${}^9\text{Be}$  abundance is found such that Be increases linearly as Fe during the course of Galactic evolution (Boesgaard et al. 1999). The first report on observation of beryllium in two very metal-poor stars with the Ultraviolet and Visible Echelle Spectrograph (UVES) mounted on the ESO VLT Kueyen telescope (Primas et al. 2000a) said that the trend of beryllium with metallicity keeps decreasing at lower metallicities with no evidence of flattening. Primas et al. (2000b) found that the very metal deficient star G 64-12 ( $[\text{Fe}/\text{H}] = -3.3$ ) has Be of  $\log(\text{Be}/\text{H}) = -13.10 \pm 0.15$  dex, which is significantly higher than expected from the previous trend, and claimed that this high  $[\text{Be}/\text{Fe}]$  ratio may suggest a flattening in the beryllium evolutionary trend at the lowest metallicity end or the presence of dispersion at early epochs of the Galactic evolution. On the other hand, Boesgaard & Novicki (2006) found that G64-37 with  $[\text{Fe}/\text{H}] = -3.2$  has a Be abundance which is consistent with the Be-Fe trend, and suggested that different Be values are indicative of a Be dispersion even at the lowest metallicities.

B abundances in metal-poor stars have been estimated by observations with the Goddard High Resolution Spectrograph (GHRS) on board the *Hubble Space Telescope* (HST) (Duncan et al. 1997; Garcia Lopez et al. 1998; Primas et al. 1999; Cunha et al. 2000). The boron abundances are also found to show a linear increase with a slope of  $\sim 1$  with respect to metallicity, and there is no signature of a primordial plateau abundance.

These trends of Be and B abundances are explained by Galactic CR nucleosynthesis models of different types. One is the acceleration of metal-rich CRs, probably freshly synthesized matter at SNe followed by the primary reactions between CR accelerated CNO nuclides and interstellar nuclides  $p$  and  $\alpha$ , i.e.  $[\text{CNO}]_{\text{CR}} + [p\alpha]_{\text{ISM}} \rightarrow [\text{LiBeB}]$  (e.g. Ramaty et al. 1997). This mechanism leads to the same-rate increase of BeB and O. Fields et al. (2000) have suggested that the secondary reactions between CR accelerated  $p\alpha$  and interstellar CNO i.e.  $[p\alpha]_{\text{CR}} + [\text{CNO}]_{\text{ISM}} \rightarrow [\text{LiBeB}]$ , perhaps without any contribution of the primary reactions, would explain the BeB to Fe trend if the ratio O/Fe increases toward low metallicity. Valle et al. (2002) have shown that the multi-zone (halo, thick disk, and thin disk) Galactic evolution model including only the secondary reactions can reproduce the linear trend without fine-tuning.

In this work, I adopted Model 1 and the rapid burst model of Daigne et al. (2006) for the cosmic chemical evolution model. This chemical evolution model and

other inputs, as well as calculation of light element evolution are explained in Sec. 2. I present results of the CCR nucleosynthesis in Sec. 3, and discuss this study in Sec. 4. I summarize the CCR production of LiBeB in Sec. 5.

## 2. MODEL

### 2.1. Cosmic SN Rate

I adopt the cosmic SFRs in a chemical evolution model given by Daigne et al. (2006). I take Model 1 and the rapid burst model, which include formation of stars with masses between 40 and  $100 M_{\odot}$  in the early phase of the universe. As their best model, a parameter, the minimum mass  $M_{\text{min}}$  of dark matter halos of star-forming structures is determined to be  $10^7 M_{\odot}$  for chemical evolution of structures. The adopted models are the same as Rollinde et al. (2006) use. The birthrate function is given by

$$B(m, t, Z) = \phi_1(m)\psi_1(t) + \phi_2(m)\psi_2(Z), \quad (1)$$

where  $m, t, Z$  are the mass of star, the age of the universe, and the metallicity,  $\phi_1$  and  $\phi_2$  are initial mass functions (IMFs) of the normal and massive-only component of stars, respectively,  $\psi_1$  and  $\psi_2$  are SFRs for respective components. The normal component is given such that its mass range is from 0.1 to  $100 M_{\odot}$ . The massive component is active only at high redshift, and its mass range is from 40 to  $100 M_{\odot}$ . The IMF of both modes is given by a power law of mass with an index like the Salpeter's,

$$\phi_i(m) \propto m^{-(1+x)}, \quad (2)$$

with  $x = 1.3$ . The amplitudes of the IMFs are normalized respectively as

$$\int_{m_{\text{inf}}}^{m_{\text{sup}}} dm m \phi_i(m) = 1, \quad (3)$$

where  $m_{\text{inf}}$  and  $m_{\text{sup}}$  are the lower and upper ends for the mass range of each mode.

The normal-mode SFR is given by

$$\psi_1(t) = \nu_1 M_{\text{struct}} \exp(-t/\tau_1), \quad (4)$$

where  $\nu_1 = 0.2 \text{ Gyr}^{-1}$  describes the efficiency of the star formation, and  $M_{\text{struct}}$  and  $\tau_1 = 2.8 \text{ Gyr}$  are mass of the structure and timescale, respectively.

In Model 1, the massive-mode SFR is given by

$$\psi_2(t) = \nu_2 M_{\text{ISM}} \exp(-Z_{\text{IGM}}/Z_{\text{crit}}), \quad (5)$$

where  $\nu_2 = 80 \text{ Gyr}^{-1}$  is related to the efficiency of star formation.  $M_{\text{ISM}}$  is the baryonic mass of the ISM.  $Z_{\text{IGM}}$  is the metallicity of the medium between the collapsed structures (identified as the IGM), and  $Z_{\text{crit}} = 10^{-4} Z_{\odot}$  determines the effective epoch of the end of Pop III star formation. In contrast, in the rapid burst model, the massive mode star formation occurs as an instantaneous event at redshift  $z = 16$ . Since the SFR in the model has an instantaneous bump and I found difficulty reading it from Fig. 13 of Daigne et al. (2006), I fixed the SFR so that it is  $\sim 20 M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$  during  $3 \times 10^6 \text{ yr}$  (Rollinde et al. 2006).

### 2.2. LiBeB Production in the Homogeneous Universe

I calculate abundances of light elements (LiBeB) produced in the homogeneous universe through the interaction between fast nuclei accelerated in the SN shocks and background nuclei. The picture of CCRs, i.e., the total kinetic energy of CRs and the propagation is identical to that of Rollinde et al. (2006).

### 2.2.1. CCR Energy and Its Spectrum

The total kinetic energy given to accelerated CRs by SN explosions is

$$\mathcal{E}_{\text{SN}}(z) = (1+z)^3 \times \int_{\max(8M_{\odot}, m_d(t))}^{m_{\text{sup}}} dm \sum_{i=1}^2 \phi_i(m) \psi_i(t - \tau(m)) \mathcal{E}_{\text{CR}}(m), \quad (6)$$

where  $m_d(t)$  is the mass of stars with lifetime  $t$ ,  $\tau(m)$  is the lifetime of a star of mass  $m$ , and  $\mathcal{E}_{\text{CR}}(m)$  is the energy imparted to CRs per SN with its initial mass  $m$ . Daigne et al. (2004, 2006) adopt stellar lifetimes  $\tau(m)$  from Maeder & Meynet (1989) for intermediate-mass stars ( $< 8 M_{\odot}$ ), and those from Schaerer (2002) for massive stars ( $8 M_{\odot} < m < 100 M_{\odot}$ ).

Rollinde et al. (2006) give  $\mathcal{E}_{\text{CR}}(m)$  after some assumptions to calculate the total kinetic energy  $\mathcal{E}_{\text{SN}}(z)$ . Core collapse SNe are supplied with energy by the gravitational collapse of cores. Almost all of the energy generated from core collapse,  $E_{\text{CC}}$  is transferred out by neutrinos. Only 1 % will be given to the energy of SN explosions. Rollinde et al. (2006) use a parameterization

$$\mathcal{E}_{\text{CR}}(m) = \frac{\epsilon E_{\text{CC}}(m)}{100}, \quad (7)$$

where  $\epsilon$  is the fraction of SN explosion energy imparted to CRs. Assumptions related to  $E_{\text{CC}}$  are as follows: Every star of mass  $m > 8 M_{\odot}$  explodes as SN. Stars of mass  $8 M_{\odot} < m < 30 M_{\odot}$  make neutron stars of mass  $1.5 M_{\odot}$  at core collapses and  $E_{\text{CC}} = 3 \times 10^{53}$  ergs. Stars of mass  $30 M_{\odot} < m < 100 M_{\odot}$  become black holes with masses very similar to their helium core mass (Heger et al. 2003). The mass of the helium core is  $M_{\text{He}} = 13(m - 20 M_{\odot})$  (Heger & Woosley 2002). In this case  $E_{\text{CC}}$  is proportional to the mass of the black hole, and  $E_{\text{CC}} = 0.3 M_{\text{He}}$  is assumed.

I calculate light element production in the formalism of Montmerle (1977) and Rollinde et al. (2005, 2006). The proper source function of SN CRs  $Q_i(E, z)$  in a rapid burst at redshift  $z_s$  (corresponding time  $t_s$ ) is defined as

$$Q_i(E, z) = (1+z_s)^3 C(z_s) \frac{\phi_i(E, z_s)}{\beta} \delta(t - t_s) \quad \text{[(GeV/nucleon)}^{-1} \text{ cm}^{-3} \text{ s}^{-1}\text{]}, \quad (8)$$

where  $E$  and  $\beta$  are the kinetic energy and velocity of CRs, respectively, and I define the CR injection spectrum of nuclide  $i$  as

$$\phi_i(E, z_s) = K_{ip}^{\text{CR}}(z_s) \frac{1}{(E(E + 2E_0))^{\gamma/2}}, \quad (9)$$

where  $K_{ip}^{\text{CR}}$  is the ratio of number abundance of  $i$  to that of  $p$ , i.e.  $i/p$  of CRs, and  $E_0 = 938$  GeV is the nuclear mass energy per nucleon. The amplitude of the source function is set so that SNe from both the normal mode (Pop II) and the massive mode (Pop III) stars supply the CR energy,

$$\mathcal{E}_{\text{SN}}(z) = \int_{E_{\text{min}}}^{E_{\text{max}}} E \sum_i Q_i(E, z) dE. \quad (10)$$

I take  $E_{\text{min}} = 0.01$  MeV,  $E_{\text{max}} = 10^6$  GeV, and CR spectral index  $\gamma = 3$  as Rollinde et al. (2006) do. Since the

evolution of CR confinement by a magnetic field is difficult to estimate (Rollinde et al. 2006), as a first step, I assume that the CR confinement is ineffective in the early universe, so that all CRs generated by SNe in structures immediately escape from structures to the IGM. In this case, there is uniformity of the CR density in the universe.

### 2.2.2. Primary Light Element Production by SN CRs

I define the number density of a CR species  $i$  of energy  $E$  at redshift  $z$  as  $N_i(E, z)$  [in  $\text{cm}^{-3}$  (GeV/nucleon) $^{-1}$ ]. In order to delete the volume changing effect by cosmic expansion, I define the relative number abundance to that of the background proton  $n_{\text{H}}(z)$ ,

$$N_{i,\text{H}}(E, z) \equiv N_i(E, z)/n_{\text{H}}(z). \quad (11)$$

The transport equation for  $N_{i,\text{H}}$ , under the isotropic condition, is (Montmerle 1977)

$$\frac{\partial N_{i,\text{H}}}{\partial t} + \frac{\partial}{\partial E}(b N_{i,\text{H}}) + \frac{N_{i,\text{H}}}{T_{\text{D}}} = Q_{i,\text{H}}, \quad (12)$$

where  $b(E, z) \equiv (\partial E / \partial t)$  is the energy loss rate [(GeV/nucleon)  $\text{s}^{-1}$ ] for cosmic expansion or ionization, and  $T_{\text{D}}(E, z)$  is the lifetime against destruction.  $Q_{i,\text{H}}(E, z) \equiv Q_i(E, z)/n_{\text{H}}(z)$  is the normalized comoving source function.

The expansion loss and ionization loss are expressed in a product of energy-dependent term and a redshift-dependent one,  $b(E, z) = -B(E)f(z)$ . These terms are given in Montmerle (1977). The redshift-dependent term of the expansion loss is  $f_{\text{E}} = (1+z)^{-1} |dz/dt| H_0^{-1}$ , where  $H_0$  is the Hubble constant. I assume the standard  $\Lambda$ CDM model with its parameters from WMAP three-year data (Spergel et al. 2007)<sup>3</sup>,  $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.704$ ,  $\Omega_b h^2 = 0.022$ ,  $\Omega_m = 0.27$ ,  $\Omega_{\Lambda} = 0.73$ . The ionization loss rate is from the fitting formula in Meneguzzi et al. (1971) with the number fraction of  $^4\text{He}$ ,  $\text{He}/\text{H} = 0.08$ .  $T_{\text{D}} = (n_{\text{H}}(z) \sigma_{\text{D},i} \beta)^{-1}$  is estimated with the nuclear destruction cross section  $\sigma_{\text{D},i}$  from Reeves (1974).

I define  $z^*(E, E', z)$  as in Montmerle (1977),

$$\frac{\partial z^*}{\partial E} = -\frac{1}{B(E)f(z)} \left| \frac{dz}{dt} \right| \frac{\partial z^*}{\partial z}. \quad (13)$$

A physical interpretation is that a CR particle with energy  $E$  at redshift  $z$  had an energy  $E'(\geq E)$  at redshift  $z^*(E, E', z)$  before experiencing energy loss. Thus  $z^*(E, E, z) = z$  is satisfied. CCR particles with energy  $E$  at  $z$  originate in those with  $E'_s(E, z, z_s)$  at  $z_s$ .  $E'_s(E, z, z_s)$  satisfies an equation,  $z^*(E, E'_s, z) = z_s$ .  $z^*(E, E', z)$  is obtained by integrating Eq. (13) applying the greater loss process to  $b$  assuming that the process with the greater rate of  $b(E, z)$  is dominant all the way from redshift  $z^*$  to  $z$ .

The transfer equation is solved (Montmerle 1977) to obtain the CCR energy spectrum from a CR burst at  $z_s$ ,

$$\Phi_{i,\text{H}}(E, z, z_s) = C(z_s) \frac{\phi_i(E'_s, z_s)}{n_{\text{H}}^0} \frac{\beta}{\beta'} \left| \frac{dz}{dt} \right|_{z_s} \times \frac{\exp(-\xi(E, E'_s, z))}{|b(E, z_s)|} \frac{1}{|\partial z^* / \partial E'|_{E'_s}}, \quad (14)$$

<sup>3</sup> <http://lambda.gsfc.nasa.gov>

where  $\Phi_{i,H}(E, z, z_s) \equiv \Phi_i(E, z, z_s)/n_H(z)$  is the normalized flux of  $i$  per comoving volume with  $\Phi_i(E, z, z_s) \equiv \beta N_i(E, z, z_s)$ ,  $\beta$  and  $\beta'$  are the velocities corresponding to energy  $E$  and  $E'$ , respectively.  $n_H^0$  is the present average number density of protons in the universe.  $\xi$  is an effect resulting when the nuclear destruction is considered, and given as

$$\xi(E, E'_s, z) = \int_E^{E'_s} \frac{dE''}{|b(E'', z^*(E, E'', z))T_D(E'', z^*(E, E'', z))|}. \quad (15)$$

After analysis with Eq. (13), one can estimate  $|\partial z^*/\partial E'|_{E'=E'_s} = |b(E'_s, z_s)|^{-1}|dz/dt|_{z=z_s}$  and find an expression for  $\Phi_{i,H}$

$$\Phi_{i,H}(E, z, z_s) = C(z_s) \frac{\phi_i(E'_s, z_s)}{n_H^0} \frac{\beta}{\beta'} \frac{|b(E'_s, z_s)|}{|b(E, z_s)|} e^{-\xi(E, E'_s, z)}. \quad (16)$$

The production rate of light element  $l$  of energy  $E$ , produced at redshift  $z$  is given by

$$\begin{aligned} \frac{\partial N_{l,H}(E, z, z_s)}{\partial t} &= \sum_{i,j} \int \sigma_{ij \rightarrow l}(E, E') n_j(z) \Phi_{i,H}(E', z, z_s) dE' \\ &= \sum_{i,j} \int \sigma_{ij \rightarrow l}(E, E') K_{jp}^{\text{IGM}}(z) \Phi_i(E', z, z_s) dE', \end{aligned} \quad (17)$$

where  $\sigma_{ij \rightarrow l}(E, E')$  is a cross section of a process between a CR nuclide  $i$  with energy per nucleon  $E'$  and a background species  $j$  to make a given light element  $l$  with  $E$ , and  $n_j(z)$  and  $K_{jp}^{\text{IGM}}(z)$  are background number abundance of a nuclide  $j$  and number ratio of  $j$  to proton, respectively. When the destruction of the light element  $l$  after production is neglected, the total production rate is calculated as

$$\begin{aligned} \int \frac{\partial N_{l,H}(E, z, z_s)}{\partial t} dE \\ = \sum_{i,j} K_{jp}^{\text{IGM}}(z) \int \sigma_{ij \rightarrow l}^{\text{tot}}(E') \Phi_i(E', z, z_s) dE', \end{aligned} \quad (18)$$

where  $\sigma_{ij \rightarrow l}^{\text{tot}}(E')$  is the total cross section of a reaction  $i + j \rightarrow l + X$ , with any  $X$ . I adopt cross sections from Read & Viola (1984), and particularly for the  $\alpha + \alpha$  reaction, exponential-plus-constant cross section for  $l = {}^6\text{Li}$  and exponential one for  $l = {}^7\text{Li}$  from Mercer et al. (2001). The resulting light element abundance is obtained as the CR production added to the BBN yield. The yield by CR nucleosynthesis is the integration of those produced at  $z'$  from CRs generated at  $z_s$  over  $z'$  and  $z_s$ , thus

$$\begin{aligned} \left(\frac{l}{H}\right)_{\text{IGM}}(z) &= \left(\frac{l}{H}\right)_{\text{BBN}} \\ &+ \int_z^{z_{\text{max}}} dz_s \left| \frac{dt}{dz_s} \right| \int_z^{z_s} dz' \left| \frac{dt}{dz'} \right| \\ &\times \sum_{i,j} K_{jp}^{\text{IGM}}(z') \int \sigma_{ij \rightarrow l}^{\text{tot}}(E') \Phi_i(E', z', z_s) dE'. \end{aligned} \quad (19)$$

### 2.2.3. Secondary Light Element Production by SN CRs

I also calculate the LiBeB production in the universe by the secondary process, i.e.,  $[p\alpha]_{\text{CR}} + [\text{CO}]_{\text{ISM}} \rightarrow [\text{LiBeB}]_{\text{ISM}}$ . Since the C and O abundances of the ISM in structures are about two orders of magnitude higher than those of the IGM (see Fig. 11 in Daigne et al. 2006), the secondary LiBeB production in the IGM is not important. I expect that the LiBeB abundances in the ISM are enhanced by a contribution of the secondary process. In fact, the reactions of  $[p\alpha]_{\text{CR}} + [\text{CO}]_{\text{ISM}} \rightarrow [\text{LiBeB}]_{\text{ISM}}$  make light elements in the ISM and the mass accretion to the structures from the IGM dilutes the ISM abundances in the framework of this model involving a hierarchical structure formation. Note that from the assumption that the confinement of CRs by a magnetic field is ineffective, the CRs do not stay in the structures.

The light element abundances produced by the secondary reactions are then given with a parameter: the fraction of baryons at redshift  $z$  which are in structures

$$f(z) = \frac{\int_{M_{\text{min}}}^{\infty} dM M f_{\text{PS}}(M, z)}{\rho_{\text{DM}}}, \quad (20)$$

where  $f_{\text{PS}}(M, z)$  is the distribution function of halos taken from the Sheth & Tormen (1999) modification to the Press-Schechter function (Press & Schechter 1974) converted into the mass function (Jenkins et al. 2001) by a code provided by A. Jenkins (2007, private communication). I assume that the primordial power spectral slope is  $n=1$ , the rms amplitude for mass density fluctuations in a sphere of radius  $8 h^{-1}$  Mpc is  $\sigma_8 = 0.9$ , and the Bond & Efstathiou (1984) fit to the transfer function for cold dark matter is used in generating a mass function.  $\rho_{\text{DM}}$  is the comoving dark matter density of the universe.

The light elements made by the secondary process are contained in the structures that grow gradually. The abundance of a light element in the structures is then given by

$$\begin{aligned} \left(\frac{l}{H}\right)_{\text{ISM}}(z) &= \left(\frac{l}{H}\right)_{\text{IGM}}(z) \\ &+ \frac{1}{f(z)} \int_z^{z_{\text{max}}} dz_s \left| \frac{dt}{dz_s} \right| \int_z^{z_s} dz' \left| \frac{dt}{dz'} \right| \\ &\times \sum_{i,j} K_{jp}^{\text{ISM}}(z') f(z') \int \sigma_{ij \rightarrow l}^{\text{tot}}(E') \Phi_i(E', z', z_s) dE'. \end{aligned} \quad (21)$$

## 3. RESULTS

I calculate the light element production in the uniform universe by CCRs (i.e. neglecting an inhomogeneity of CCRs). I consider only processes between the accelerated CRs with the abundance patterns of the structures in the Daigne et al. (2006) model and the background IGM abundance which I assumed to be of the primordial abundance. I set the primordial helium abundance  $\text{He}/\text{H}=0.08$ .

I show the result of light element evolution in Model 1 in Fig. 1. Solid lines correspond to the case where both the normal and massive modes are included, and dashed lines correspond to the case in which only the normal mode is included as the energy source. When the SN energy is totally given to the CR acceleration ( $\epsilon = 1$ ),  ${}^6\text{Li}/\text{H}=2.0 \times 10^{-11}$  at  $z = 3$  is derived. In Fig. 1,  $\epsilon = 0.31$

is assumed so that  ${}^6\text{Li}/\text{H}=6 \times 10^{-12}$  at  $z = 3$  results that is the observed abundance level in MPHSs. In the case that the CRs are energized by only the normal mode star formation, the energy fraction  $\epsilon = 0.73$  is needed to realize the observed  ${}^6\text{Li}$  abundance. The time evolution of light element abundances in the rapid burst model is shown in Fig. 2. The energy fraction given to the CR acceleration is assumed to be  $\epsilon = 0.029$ , and the abundance of  ${}^6\text{Li}$  gets  ${}^6\text{Li}/\text{H}=6 \times 10^{-12}$  at  $z = 3$ . These results are very similar to that in Rollinde et al. (2006) (See their Fig. 2). In Model 1,  ${}^6\text{Li}$  is produced gradually with decreasing redshift, while in rapid burst model, it is immediately produced by most part at the burst of star formation. In my calculation, the  ${}^6\text{Li}$  production at high redshift tends to be slightly more efficient than in Rollinde et al. (2006). This difference might be caused by different numerical calculation of transport equation for nuclides.

Figure 3 shows the yields by CCRs generated at  $z_s$  per second in Model 1, i.e.  $\Delta(l/\text{H})/\Delta t_s$ . The calculated results show that  ${}^6\text{Li}$  and  ${}^7\text{Li}$  are produced mainly by the  $\alpha + \alpha$  fusion reaction, and Be and B production has the strongest contribution from the  $\text{O}+p$  (and  $\text{C}+p$ ) spallation processes. I have taken the helium abundance  $\text{He}/\text{H}=0.08$ , and the O abundance in the ISM of structures in Model 1 is roughly constant from  $z \sim 0$  to  $z \sim 20$  (see Fig. 11 of Daigne et al. 2006). The injected energy density in CRs is smoothly increasing as a function of redshift  $z$  (Fig. 2 of Rollinde et al. 2006). This figure therefore reflects the abundance of seed nuclides and injected energy density. The CRs generated at  $z_s \sim 3$  have little time to react with background nuclear species, so that the yields go to zero, and a decrease in all yields at  $z_s \lesssim 25$  reflects the shape of CR energy density (Fig. 2 of Rollinde et al. 2006).

I assume that MPHSs formed at redshift  $z \sim 3$  and that they include LiBeB elements at the level of the IGM abundances at the time. If one can neglect the inhomogeneity of CCRs resulting from the local growth of a magnetic field, numbers of produced elements are proportional to target particle numbers. Consequently, resulting light element abundance  $l/\text{H}$  does not depend on density there. Although the metallicities like  $\text{Fe}/\text{H}$  of metal-poor stars reflect how the metal-enhanced and metal-deficient gas are mixed before star formation, the light element abundances are constant for the same formation epoch. In this case, there appear primordial plateaus on the plot of abundances as a function of metallicity  $[\text{Fe}/\text{H}]$ . The energy fractions given to the CR acceleration,  $\epsilon = 0.31$  for Model 1 and  $\epsilon = 0.029$  for the rapid burst model realize the observed abundance of  ${}^6\text{Li}$  in MPHSs at  $z = 3$ . These fractions are reasonable, considering that the energy of Galactic CRs can be covered by 10 – 30 percent of supernova remnant (SNR) energy (Drury et al. 1989). If  ${}^6\text{Li}$  observed in MPHSs is produced mainly by this CCR nucleosynthesis, these stars include Be and B which had been coproduced.

In Fig. 4 the plateau levels of  ${}^6\text{Li}$  and  ${}^7\text{Li}$  in Model 1 are drawn with observational data points in a plot of abundances as a function of metallicity  $[\text{Fe}/\text{H}]$ . As for the  ${}^7\text{Li}$  abundance, the BBN prediction is calculated using the Kawano code (Kawano 1992) with the use of the new world average of the neutron lifetime (Mathews et al. 2005). I take the energy den-

sity of baryons in the universe given by WMAP first year data analysis (Spergel et al. 2003) that is  $\Omega_b h^2 = 0.0224 \pm 0.0009$ . This value corresponds to the baryon-to-photon ratio  $\eta = 6.1 \times 10^{-10}$ . The predicted abundance is then  $({}^7\text{Li}/\text{H})_{\text{BBN}}=4.5 \times 10^{-10}$ . The  ${}^7\text{Li}$  production by the CCR nucleosynthesis is a minor addition to the BBN result. The figure for the rapid burst model is very similar to Fig. 4. The factor of about three difference between the BBN prediction and the observation of  ${}^7\text{Li}$  abundance is apparent.

The coproduced abundance levels of Be and B in Model 1 are shown in Fig. 5 with observational data points. It is interesting that the predicted abundance levels of Be and B are located at nearly the lowest point ever detected. This model predicts primordial plateau abundances of Be and B as an analog of the likely  ${}^6\text{Li}$  plateau. If future observation of beryllium in metal-poor stars catches evidence of a plateau abundance, it would be explained by this CCRs origin. When the normal mode star formation alone is taken as the CR energy source, the result is consistent with the observed abundance of  ${}^6\text{Li}$  in MPHSs at  $z = 3$  with  $\epsilon = 0.73$ . This case corresponds to dashed lines in Fig. 5. In the same way, the coproduced abundances in the rapid burst model with  $\epsilon = 0.029$  are shown as the dotted lines. This calculation shows that Be and B abundances are somewhat higher in the rapid burst model than in Model 1 relative to that of  ${}^6\text{Li}$ . This calculation seems possibly to contain an error of the order of  $\sim 10\%$  in Be and B abundances associated with the reading of a very brief burst of SFR (Fig. 13 of Daigne et al. 2006) and resulting sudden enrichment of C and O in the ISM of structures (Fig. 16 of Daigne et al. 2006, arXiv:astro-ph/0509183) as input profiles in this calculation. In the cosmic chemical evolution model of Daigne et al. (2006), the rapid burst of star formation occurs in a very brief time and C and O abundances in structures increase accordingly reflecting the ejection of C and O nuclei by SNe. Since Be and B production is sensitive to the CR energy density times C and O abundances in structures, the fine-meshed time evolution of C and O abundances as well as CR energy density (which is associated with SN rate) is necessary to perform a precise calculation. However, since the rapid burst model gives sudden rises of C and O abundances, and C and O particles are accelerated before the ISM abundances can be somewhat diluted by accretion of the IGM, abundances of C and O in CCRs are relatively high. Then it is as expected that the rapid burst model produces more Be and B relative to  ${}^6\text{Li}$  than in Model 1, considering that Be and B are produced by spallation processes of C and O while lithium isotopes are produced mainly by  $\alpha + \alpha$  fusion. I show the results of calculations of light element production in the CCR nucleosynthesis model in Table 1. In the second column, values of energy fraction of SNRs given to CR acceleration required to produce  ${}^6\text{Li}$  at the observed level in MPHSs at  $z = 3$  are shown. The resulting abundances of light elements with the CR acceleration efficiencies in the second column are listed in the third to seventh columns.

In the calculations so far, the spectral index of the CR injection spectrum has been fixed to  $\gamma = 3$ . I show the energy fraction of SNRs to CRs,  $\epsilon$ , required to produce  ${}^6\text{Li}$  at the MPHSs level at  $z = 3$  as a function of  $\gamma$  in Fig. 6. The solid line corresponds to Model 1 and the

dashed line to the case where only the normal mode stars are considered as the energy source of CCRs. One can see that the required energy fraction  $\epsilon$  is reasonable if  $2.7 \lesssim \gamma \lesssim 3.1$ . Meanwhile, smaller spectral index of  $\gamma \lesssim 2.7$  could not produce enough  ${}^6\text{Li}$  in this model.

Figure 7 shows abundances of Be and B at  $z = 3$  as a function of  $\gamma$  in Model 1 with the value of  $\epsilon$  in Fig. 6, i.e., when  ${}^6\text{Li}$  is produced at the MPHSs level. It is found that relative produced abundances of Be and B are decreasing functions of  $\gamma$ . In other words, the steeper the momentum spectrum of CRs is, the more  ${}^6\text{Li}$  is produced relatively. In the region  $2.7 \lesssim \gamma \lesssim 3.1$ , where the  ${}^6\text{Li}$  abundance produced in this model can attain the MPHSs level with a reasonable partition of SNR energy to CR acceleration,  $\log(\text{Be}/\text{H}) \sim -13.1 - -12.9$  and  $\log(\text{B}/\text{H}) \sim -12.0 - -11.8$  are obtained. These abundances are again near the least abundances detected in metal-poor stars.

Figure 8 shows the abundances of light elements produced by the secondary process in the ISM as a function of redshift in Model 1 calculated by the second term in the rhs of Eq. (21).  $\epsilon = 0.31$  is assumed to result in  ${}^6\text{Li}/\text{H} = 6 \times 10^{-12}$  in the IGM at  $z = 3$ . Solid lines correspond to the case where both the normal and massive modes are included, and dashed lines correspond to a contribution of the normal mode as the energy source. The contributions of primary and secondary processes to the light element synthesis in the ISM are estimated by the comparison between Fig. 1 and Fig. 8. Since  ${}^6\text{Li}$  and  ${}^7\text{Li}$  are produced mainly by the  $\alpha + \alpha$  fusion which I contained in the calculation of Fig. 1, the contributions of the secondary process are relatively small. On the other hand, Be and B have some contribution from the secondary process. For example, the Be and B abundances produced by the secondary process are about 25 % (65 %) of those by the primary process at  $z = 3$  in Model 1 with both the normal and massive modes (with only the normal mode). It is found that the BeB abundance levels produced by the CCR nucleosynthesis are roughly the same in the ISM and the IGM. This contribution from the secondary process is small in the rapid burst model (about 2.5 % for Be and B) at  $z = 3$ . The fraction of baryons included in the ISM is smaller at higher redshift, when the energy injection in the rapid burst model occurs. It is then easily understood that the light element abundances produced by the secondary reactions are smaller in the rapid burst model considering the dilution of light element abundances due to mass accretion by structure formation in the model.

#### 4. DISCUSSION

The resulting abundances from Eq. (18) have a clear dependence on input quantities as

$$\int \frac{\partial N_{l, \text{H}}(E, z, z_s)}{\partial t} dE \propto \sum_{i, j} \mathcal{E}_{\text{SN}}(z_s) K_{ip}^{\text{CR}}(z_s) K_{jp}^{\text{IGM}}(z). \quad (22)$$

I adopted the results of the two models of Daigne et al. (2006) as the total CRs energy by SN explosions  $\mathcal{E}_{\text{SN}}(z_s)$  and the ratio of number abundance of  $i$  to that of  $p$ , i.e.  $i/p$  of CRs  $K_{ip}^{\text{CR}}(z_s)$ , which I assume to be the same as the ISM abundance of structures. These two quantities are uncertain, in fact. I use the primordial abundance for the background number ratio of  $j$  to  $p$   $K_{jp}^{\text{IGM}}(z)$ . This quantity is reasonable and would not contain large uncer-

tainty. A large difference in  $K_{ip}^{\text{CR}}(z_s)$  ( $i = \text{C, O}$ ) leads to a difference in produced Be and B abundances linearly, while  ${}^6\text{Li}$  and  ${}^7\text{Li}$  abundances have little influence since they are mainly produced by the  $\alpha + \alpha$  fusion process.

Suzuki & Yoshii (2001) have developed a model for the evolution of light elements in the Galaxy, which includes the SN-induced chemical evolution with contributions from SNe and CRs nucleosynthesis self-consistently. They have explained the light element abundances observed in metal-poor stars using their model with the CR abundances including SN ejecta 3.5 % in mass fraction. The linear relation between  $[\text{BeB}/\text{H}]$  and  $[\text{Fe}/\text{H}]$  has been obtained by the primary process to make Be and B. Consequently their CR abundance includes the C and O in mass fraction of  $(5 - 7) \times 10^{-3}$  originating from the SN ejecta throughout the Galactic chemical evolution. On the other hand, the mass fraction of C+O is  $(3 - 10) \times 10^{-3}$  in Model 1 of Daigne et al. (2006) I adopt, which is roughly the same level of abundance as that Suzuki & Yoshii (2001) used within a factor of  $\lesssim 2$ . The CR abundance I give in this study, therefore, would be appropriate within a factor of  $\sim 2$ , even if the real C and O abundances in the ISM producing CRs were lower than I give, supposing that the CRs have contribution from the SN ejecta by the fraction inferred by Suzuki & Yoshii (2001).

I assume that all CRs escape from structures to the IGM, and do not consider a nonuniformity of the CR density in the universe. As structures grow in the universe, a magnetic field grows accordingly, and the CR flux might get inhomogeneous, especially at low redshift, while the overproduction of  ${}^6\text{Li}$  provides a constraint on the confinement of CRs in the ISM (Rollinde et al. 2006). Further study including the space distribution and time evolution of a magnetic field is desirable to estimate the light element abundances produced by the CCR nucleosynthesis.

The calculated result would also contain an uncertainty from two-step reactions, i.e., production of nuclide  $l_2$  by sequential non-thermal nuclear reactions:  $i + j \rightarrow l_1$  and  $l_1 + j_2 \rightarrow l_2$  with any nuclides  $l_1$  and  $j_2$  (Ramaty et al. 1997; Kneller et al. 2003). Kneller et al. (2003) have found that two-step reaction rates are only of the order of 1/10 smaller than one-step reaction rates. The effect of two-step reactions in the framework of this study is roughly estimated as follows. Nuclei produced by nuclear reactions experience an energy loss and nuclear destruction. If one take nuclei with kinetic energy of  $E \gtrsim 10$  MeV/nucleon, the expansion loss is dominant loss process in the considered redshift range. The time scale for expansion loss is given by

$$\begin{aligned} T_{\text{loss}} &\sim \frac{dE}{b_{\text{exp}}(E, z)} \\ &= \frac{E + E_0}{H_0(E + 2E_0)} [\Omega_m(1+z)^3 + (1 - \Omega_m)]^{-1/2} \\ &= 4.4 \times 10^{17} \text{ s} \frac{E + E_0}{(E + 2E_0)} [\Omega_m(1+z)^3 + (1 - \Omega_m)]^{-1/2}, \end{aligned} \quad (23)$$

where  $b_{\text{exp}}(E, z)$  is the energy loss rate for the cosmic expansion. On the other hand, using an empirical formula of nuclear destruction (Eq. 1 in Letaw et al. 1983), i.e.,

$\sigma = 44.9A^{0.7}$  mb, the time scale for nuclear destruction is given by

$$T_D = (n_H(z)\sigma\beta)^{-1} \\ = 8.0 \times 10^{20} \text{ s} \left(\frac{A}{10}\right)^{-0.7} (1+z)^{-3} \beta^{-1}. \quad (24)$$

Ratios of time scales for nuclides with  $A \sim 10$  and  $E = 10 - 10^6$  MeV/nucleon are  $T_{\text{loss}}/T_D \sim 10^{-3} - 10^{-2}$  at  $z = 3$ ,  $3 \times 10^{-3} - 3 \times 10^{-2}$  at  $z = 10$ , and  $10^{-2} - 0.2$  at  $z = 30$ , respectively. Therefore, the fraction at which nuclei produced by nuclear spallations experience second nuclear reactions before losing enough energy is expected to be at most of the order of  $\sim 10$  %, if the energy spectrum of CRs indicates small amount of high energy CRs. I check a fraction of high energy CRs in number, which would be estimated by

$$F(\gamma) \equiv \frac{\int_{100 \text{ MeV}}^{E_{\text{max}}} Q_i(E', z) dE'}{\int_{10 \text{ MeV}}^{E_{\text{max}}} Q_i(E', z) dE'} = \frac{P(100 \text{ MeV})}{P(10 \text{ MeV})}, \quad (25)$$

where I defined

$$P(E) \equiv \int_E^{E_{\text{max}}} \frac{E' + E_0}{[E'(E' + 2E_0)]^{(\gamma+1)/2}} dE'. \quad (26)$$

For  $\gamma = 2, 3, 4$ ,  $F(2) = 0.31$ ,  $F(3) = 0.095$ , and  $F(4) = 0.029$  are obtained, respectively. The fraction of high energy CRs is thus relatively low for the range of  $2 \leq \gamma \leq 4$ . As a result, the effect of two-step reactions is small and would be at most of the order of  $\sim 10$  %.

Rollinde et al. (2008) also study the CR production of Be and B by CCRs. Their conclusion is very similar to that of this study, and a potentially detectable Be and B is produced by CCR-induced spallation reactions at the time of the formation of the Galaxy ( $z \sim 3$ ). However, there are some differences of assumptions between the two studies, which are compared here. I give the CR spectrum of CO nuclides by the same shape as those of  $p$  and  $\alpha$  particles, while Rollinde et al. (2008) give it by a broken power law which matches the observed present-day Galactic CR spectrum. Moreover, I give the abundances of CR by those of structures in the cosmic chemical evolution model of Daigne et al. (2006), while Rollinde et al. (2008) give them by those of structures in Daigne et al. (2006) model multiplied by abundance enhancement factors of present Galactic CR fluxes. I assume that the CR confinement by a magnetic field is ineffective in the early universe, and that all CRs generated by SNe in structures escape to the IGM, while Rollinde et al. (2008) apply a shape of CR diffusion coefficient, which leads to some degrees of the nuclear destruction of CRs in structures and the application of a broken power law in the CR energy spectrum of CO nuclides. Their diffusion coefficient is derived assuming that it is given by that in a magneto-hydrodynamic (MHD) turbulence, and that the magnetic energy density is proportional to the thermal energy, and that a characteristic length scale for the magnetic field is given by the local Jeans scale. It is interesting that the two studies using different assumptions for the uncertain physical inputs arrived at the similar conclusions.

I comment on a difference between the results of this CCR production of the light elements and those of the flare production model (Tatischeff & Thibaud 2007).

The CCR nucleosynthesis leads to the production of Be and B at the lowest level ever detected, in this model calculation. The nucleosynthesis on the main sequence stars triggered by flare-accelerated nuclides, on the other hand, results in the negligible productions of  $^7\text{Li}$ , Be and B, which are proportional to the metallicity and exist at very low abundance levels under the observed linear trend as a function of metallicity. Therefore if we observe a signature of the primordial origin of Be and B by measurements of MPHSs, the production mechanism of Be and B would not be the flare-energized nuclear reactions after the star formations, and it would be thought that the plateau abundances of Be and B originate in the CCR production and  $^6\text{Li}$  has been coproduced at pregalactic phase by the CCRs.

## 5. CONCLUSIONS

The recent observations of MPHSs reveal the probable existence of high plateau abundance of  $^6\text{Li}$ , which is about a thousand times higher than predicted in the standard BBN model. Since the standard Galactic chemical evolution model with the Galactic CR nucleosynthesis gives lower values of  $^6\text{Li}$  abundance at the metallicities of the observed MPHSs, some mechanism must have produced  $^6\text{Li}$  existing in the surface of MPHSs. As a candidate of a  $^6\text{Li}$  production mechanism, the early burst of CRs has been proposed (Rollinde et al. 2005), and the nucleosynthesis by the CRs from SN explosions is calculated (Rollinde et al. 2006) in a detailed model of cosmic chemical evolution (Daigne et al. 2006) which satisfies various observational constraints including an early reionization of the universe. Rollinde et al. (2006) have found that the  $\alpha + \alpha$  fusion reaction can produce  $^6\text{Li}$  to the level observed in MPHSs.

I calculate the cosmological cosmic ray nucleosynthesis of Be and B isotopes as well as  $^6\text{Li}$  and  $^7\text{Li}$  with the use of Model 1 and the rapid burst model in Daigne et al. (2006). It is assumed that all CRs produced by SNe in the ISM escape to the IGM and the CR intensity is always homogeneous in the universe. I found that when Model 1 (the rapid burst model) of Daigne et al. (2006) is adopted for the SFR of the universe and the metal abundances of CRs, Be and B are produced at (above) the levels observed in the most metal-poor stars with detection of Be or B, if the  $^6\text{Li}$  plateau abundance is made by the same CCR nucleosynthesis. The CR acceleration energy needed to make  $^6\text{Li}$  primordial plateau abundance at the observed level is  $\sim 3 - 31$  % of the SN kinetic energy. This value is not too large in view of an inferred present fraction of the SN energy used to the CR acceleration (Drury et al. 1989). The pregalactic SN activity might have produced some level of light elements. Although the resulting abundances of light elements depend on the parameters which I fixed to the values of Daigne et al. (2006), the future measurements of metal-poor stars would show the reasonableness of this early  $^6\text{LiBeB}$  production mechanism, and might provide a signature of a primordial Be (and perhaps B) plateau. Further observations of LiBeB elements in MPHSs are highly desirable and valuable.

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#### REFERENCES

- Asplund, M., Lambert, D. L., Nissen, P. E., Primas, F., & Smith, V. V. 2006, *ApJ*, 644, 229
- Boesgaard, A. M., Deliyannis, C. P., King, J. R., Ryan, S. G., Vogt, S. S., & Beers, T. C. 1999, *AJ*, 117, 1549
- Boesgaard, A. M., & Novicki, M. C. 2006, *ApJ*, 641, 1122
- Bond, J. R., & Efstathiou, G. 1984, *ApJ*, 285, L45
- Bonifacio, P., et al. 2007, *A&A*, 462, 851
- Coc, A., Vangioni-Flam, E., Descouvemont, P., Adahchour, A., & Angulo, C. 2004, *ApJ*, 600, 544
- Cumberbatch, D., Ichikawa, K., Kawasaki, M., Kohri, K., Silk, J., & Starkman, G. D. 2007, *Phys. Rev. D*, 76, 123005
- Cunha, K., Smith, V. V., Boesgaard, A. M., & Lambert, D. L. 2000, *ApJ*, 530, 939
- Daigne, F., Olive, K. A., Silk, J., Stoeher, F., & Vangioni, E. 2006, *ApJ*, 647, 773
- Daigne, F., Olive, K. A., Vangioni-Flam, E., Silk, J., & Audouze, J. 2004, *ApJ*, 617, 693
- Drury, L. O., Markiewicz, W. J., & Voelk, H. J. 1989, *A&A*, 225, 179
- Duncan, D. K., Primas, F., Rebull, L. M., Boesgaard, A. M., Deliyannis, C. P., Hobbs, L. M., King, J. R., & Ryan, S. G. 1997, *ApJ*, 488, 338
- Fields, B. D., Olive, K. A., Vangioni-Flam, E., & Cassé, M. 2000, *ApJ*, 540, 930
- Garcia Lopez, R. J., Lambert, D. L., Edvardsson, B., Gustafsson, B., Kiselman, D., & Rebolo, R. 1998, *ApJ*, 500, 241
- Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, *ApJ*, 591, 288
- Heger, A., & Woosley, S. E. 2002, *ApJ*, 567, 532
- Inoue, S., Aoki, W., Suzuki, T. K., Kawanomoto, S., García-Pérez, A. E., Ryan, S. G., & Chiba, M. 2005, in *IAU Symp. 228, From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution*, ed. V. Hill, P. François, & F. Primas (Cambridge: Cambridge University Press), 59
- Jedamzik, K. 2000, *Phys. Rev. Lett.*, 84, 3248
- Jedamzik, K. 2004, *Phys. Rev. D*, 70, 063524
- Jedamzik, K. 2004, *Phys. Rev. D*, 70, 08351
- Jedamzik, K. 2006, *Phys. Rev. D*, 74, 103509
- Jenkins, A., Frenk, C. S., White, S. D. M., Colberg, J. M., Cole, S., Evrard, A. E., Couchman, H. M. P., & Yoshida, N. 2001, *MNRAS*, 321, 372
- Kawano, L. 1992, NASA STI/Recon Technical Report N, 92, 25163
- Kawasaki, M., Kohri, K., & Moroi, T. 2005, *Phys. Rev. D*, 71, 083502
- Kneller, J. P., Phillips, J. R., & Walker, T. P. 2003, *ApJ*, 589, 217
- Kusakabe, M., Kajino, T., & Mathews, G. J. 2006, *Phys. Rev. D*, 74, 023526
- Letaw, J. R., Silberberg, R., & Tsao, C. H. 1983, *ApJS*, 51, 271
- Maeder, A., & Meynet, G. 1989, *A&A*, 210, 155
- Mathews, G. J., Kajino, T., & Shima, T. 2005, *Phys. Rev. D*, 71, 021302
- Meléndez, J., & Ramírez, I. 2004, *ApJ*, 615, L33
- Meneguzzi, M., Audouze, J., & Reeves, H. 1971, *A&A*, 15, 337
- Mercer, D. J., et al. 2001, *Phys. Rev. C*, 63, 065805
- Montmerle, T. 1977, *ApJ*, 216, 177
- Piau, L., Beers, T. C., Balsara, D. S., Sivarani, T., Truran, J. W., & Ferguson, J. W. 2006, *ApJ*, 653, 300
- Pospelov, M. 2006, preprint (hep-ph/0605215)
- Prantzos, N. 2006, *A&A*, 448, 665
- Press, W. H., & Schechter, P. 1974, *ApJ*, 187, 425
- Primas, F., Asplund, M., Nissen, P. E., & Hill, V. 2000, *A&A*, 364, L42
- Primas, F., Molaro, P., Bonifacio, P., & Hill, V. 2000, *A&A*, 362, 666
- Primas, F., Duncan, D. K., Peterson, R. C., & Thorburn, J. A. 1999, *A&A*, 343, 545
- Ramaty, R., Kozlovsky, B., Lingenfelter, R. E., & Reeves, H. 1997, *ApJ*, 488, 730
- Read, S. M., & Viola, V. E., Jr. 1984, *Atomic Data and Nuclear Data Tables*, 31, 359
- Reeves, R. 1974, *ARA&A*, 12, 437
- Ryan, S. G., Beers, T. C., Olive, K. A., Fields, B. D., & Norris, J. E. 2000, *ApJ*, 530, L57
- Rollinde, E., Vangioni, E., & Olive, K. 2005, *ApJ*, 627, 666
- Rollinde, E., Vangioni, E., & Olive, K. A. 2006, *ApJ*, 651, 658
- Rollinde, E., Maurin, D., Vangioni, E., Olive, K. A., & Inoue, S. 2008, *ApJ*, 673, 676
- Schaerer, D. 2002, *A&A*, 382, 28
- Sheth, R. K., & Tormen, G. 1999, *MNRAS*, 308, 119
- Shi, J. R., Gehren, T., Zhang, H. W., Zeng, J. L., & Zhao, G. 2007, *A&A*, 465, 587
- Spergel, D. N., et al. 2003, *ApJS*, 148, 175
- Spergel, D. N., et al. 2007, *ApJS*, 170, 377
- Spite, F., & Spite, M. 1982, *A&A*, 115, 357
- Suzuki, T. K., & Inoue, S. 2002, *ApJ*, 573, 168
- Suzuki, T. K., & Yoshii, Y. 2001, *ApJ*, 549, 303
- Tatischeff, V., & Thibaud, J.-P. 2007, *A&A*, 469, 265
- Valle, G., Ferrini, F., Galli, D., & Shore, S. N. 2002, *ApJ*, 566, 252

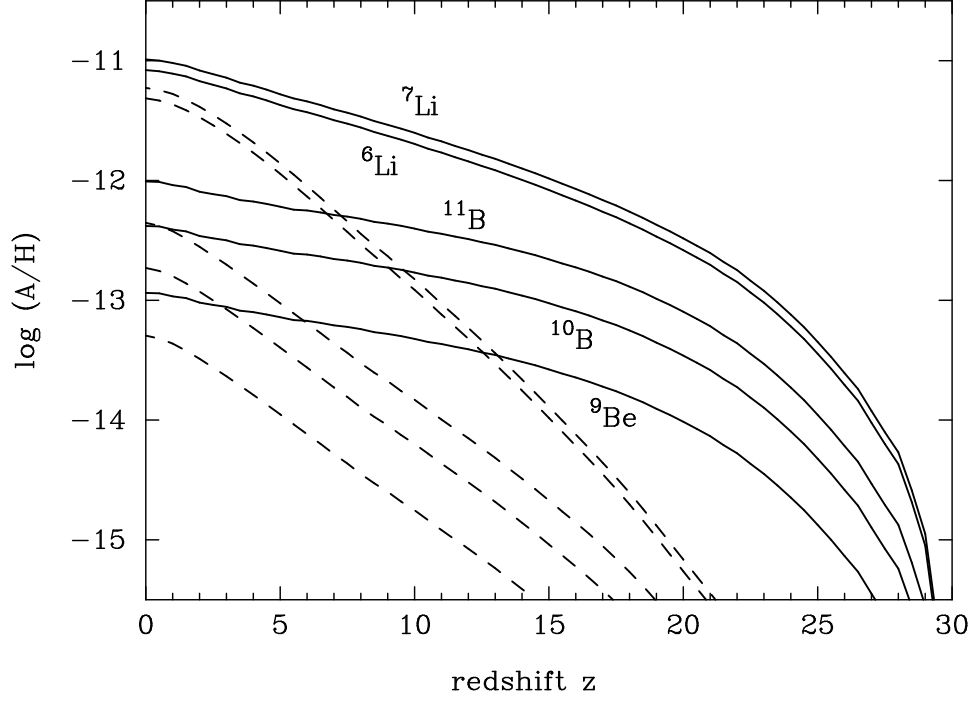


FIG. 1.— Abundances of light elements in the IGM as a function of redshift in Model 1 (solid lines).  $\epsilon = 0.31$  is assumed to result in  ${}^6\text{Li}/\text{H} = 6 \times 10^{-12}$  at  $z = 3$ . The contribution of the normal mode stars only to the light element production is shown by the dashed lines.

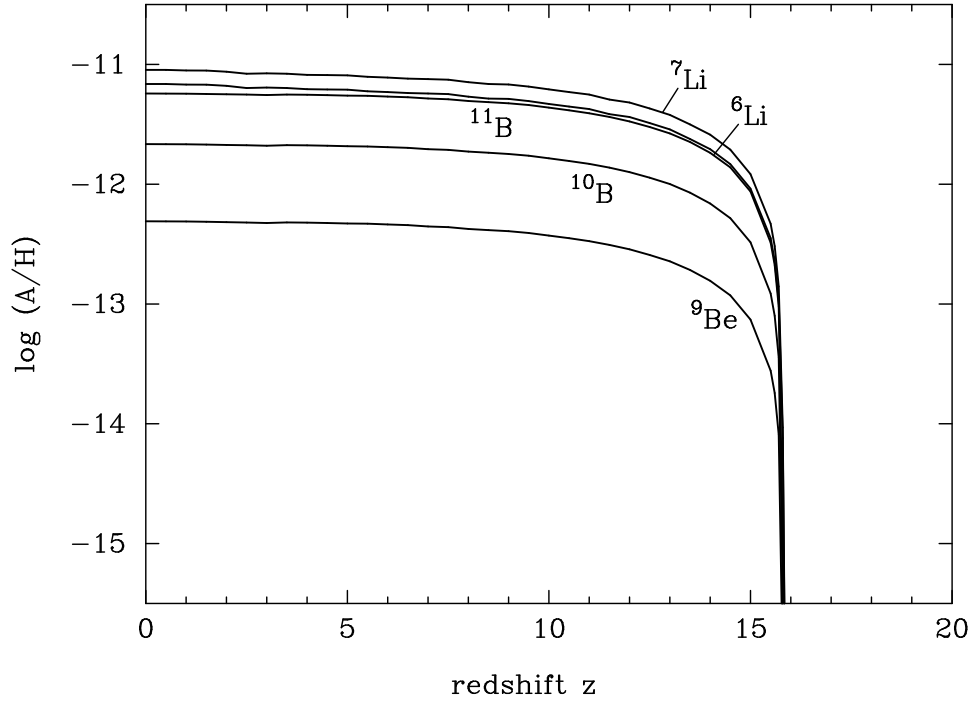


FIG. 2.— Abundances of light elements in the IGM as a function of redshift in the rapid burst model.  $\epsilon = 0.029$  is assumed to result in  ${}^6\text{Li}/\text{H} = 6 \times 10^{-12}$  at  $z = 3$ .

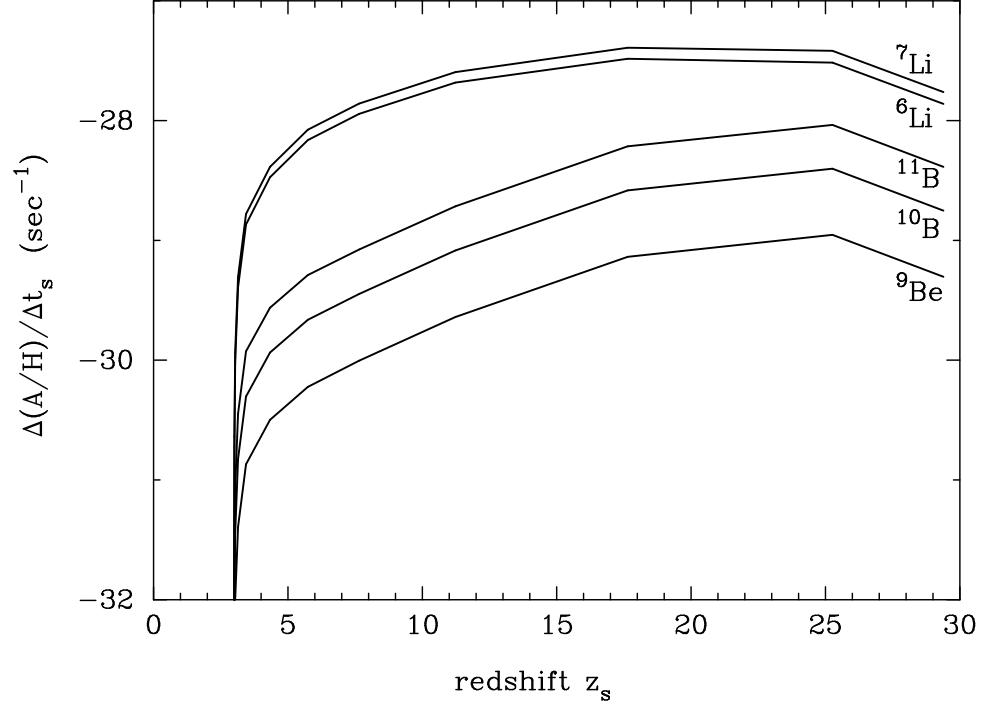


FIG. 3.— Yields of light elements at  $z = 3$  by CCRs generated at  $z_s$  per second in Model 1.

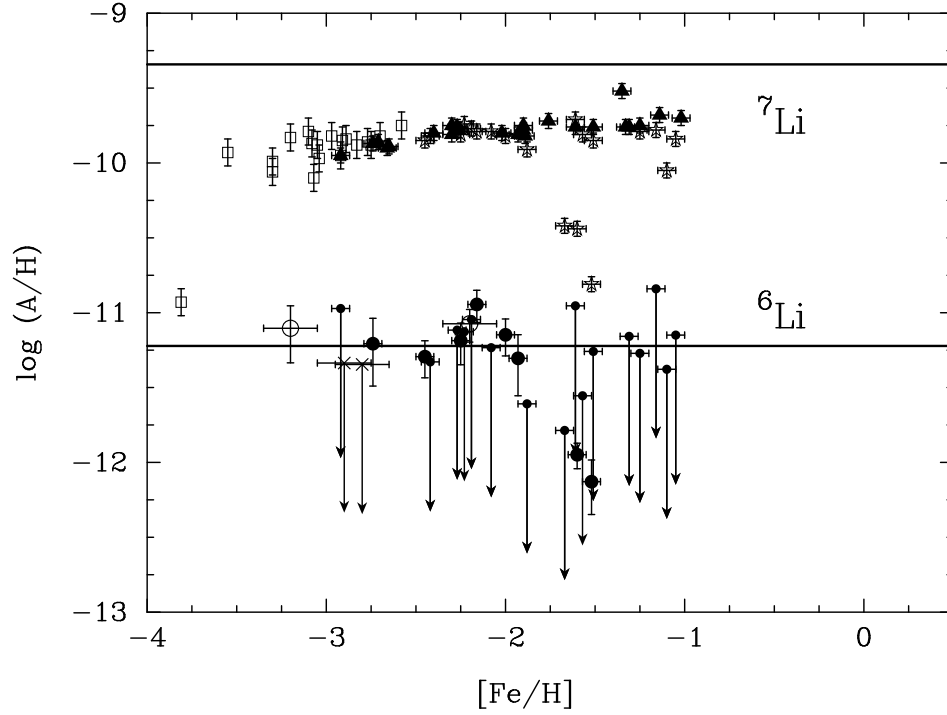


FIG. 4.— Plateau abundances of lithium isotopes produced by the CCR nucleosynthesis in Model 1 with the accelerating efficiency  $\epsilon = 0.31$ .  ${}^7\text{Li}$  data are from Asplund et al. (2006, filled triangles), Bonifacio et al. (2007, open squares), and Shi et al. (2007, open stars).  ${}^6\text{Li}$  data are from Asplund et al. (2006, large filled circles to detections, small filled circles to upper limits) and Inoue et al. (2005, open circles to detections, crosses to upper limits).

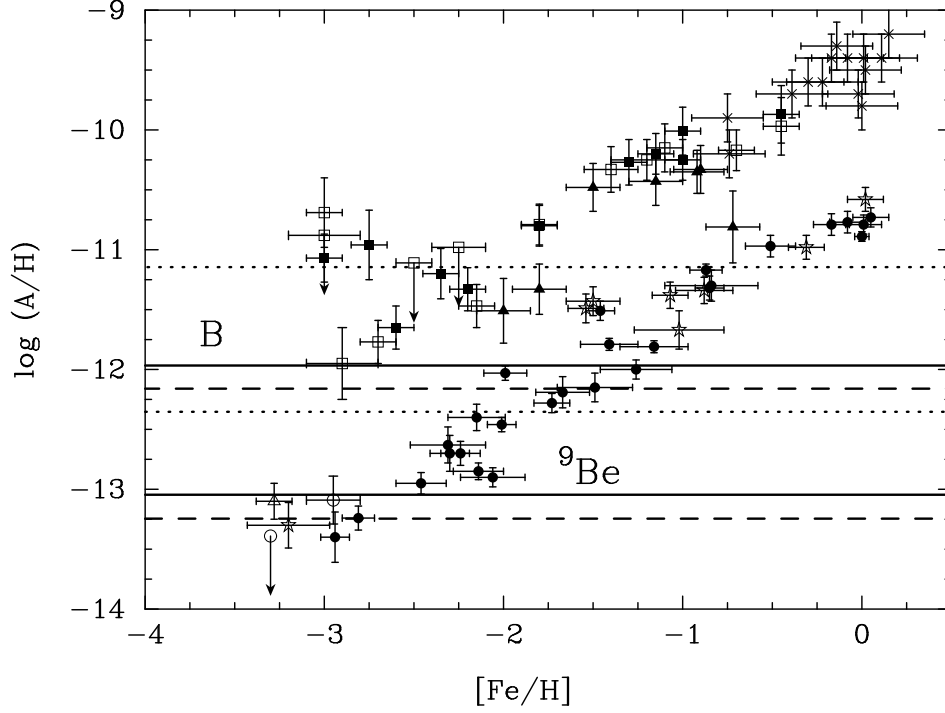


FIG. 5.— Plateau abundances of Be and B produced by the CCR nucleosynthesis in Model 1 (solid lines) with the accelerating efficiency  $\epsilon = 0.31$ . The case that the normal mode star formation alone is considered as the CR energy source corresponds to the dashed lines with  $\epsilon = 0.73$  to realize the MPHS value of  ${}^6\text{Li}$  at  $z = 3$ . Plateau abundances in the rapid burst model with the accelerating efficiency  $\epsilon = 0.029$  are also shown as the dotted lines.  ${}^9\text{Be}$  data are from Boesgaard et al. (1999, filled circles), Primas et al. (2000a, open circles), Primas et al. (2000b, open triangle), and Boesgaard & Novicki (2006, open stars). B data are from Duncan et al. (1997, filled squares), Garcia Lopez et al. (1998, open squares), Primas et al. (1999, filled triangles), and Cunha et al. (2000, crosses).

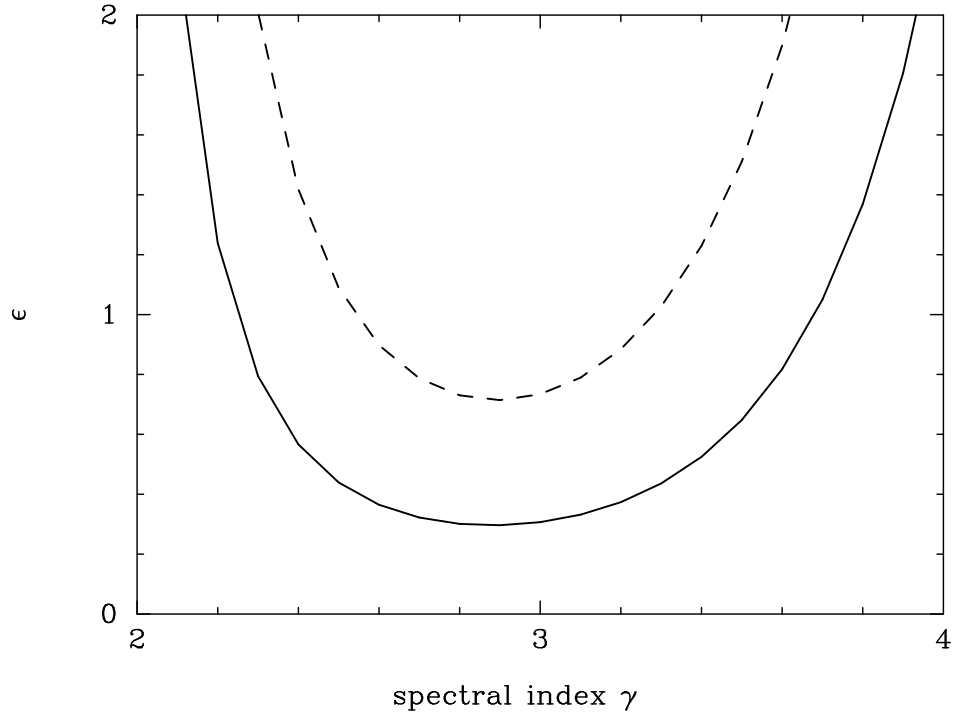


FIG. 6.— Energy fraction of SNRs to CRs,  $\epsilon$ , as a function of the index of the CR injection spectrum,  $\gamma$ , required to produce  ${}^6\text{Li}$  at the MPHSs level  ${}^6\text{Li}/\text{H} = 6 \times 10^{-12}$  at  $z = 3$ . The solid line corresponds to Model 1 and the dashed line to the case where only the normal mode stars are considered as the energy source of CCRs.

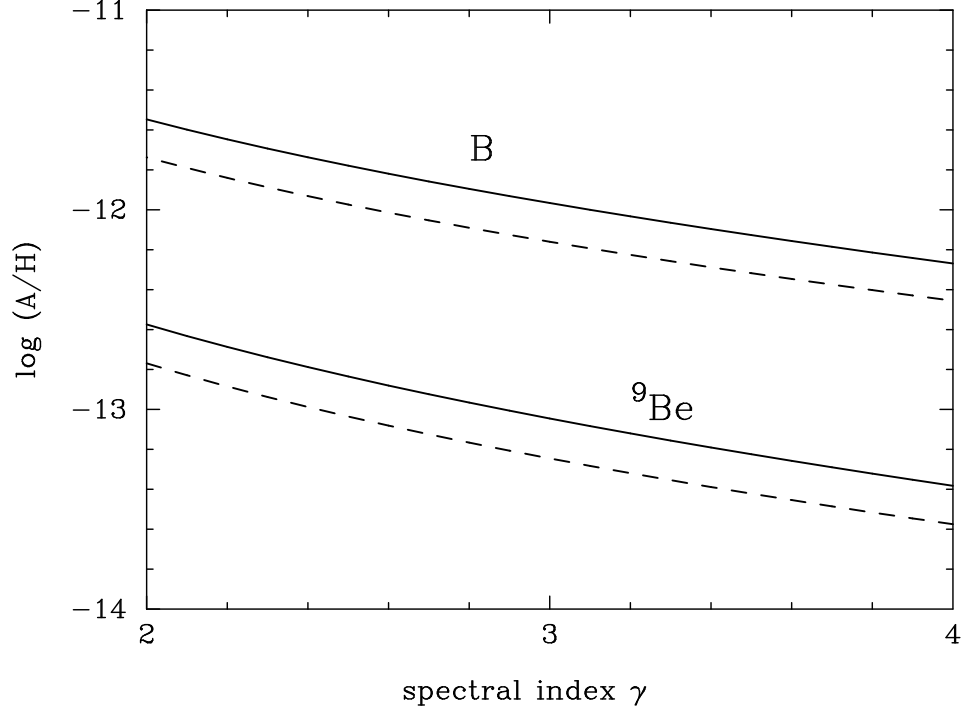


FIG. 7.— Abundances of Be and B at  $z=3$  in Model 1 with the CR energy fraction  $\epsilon$  in Fig. 6, when  $^6\text{Li}$  is produced at the MPHSs level. The solid lines correspond to Model 1 and the dashed lines to the case where only the normal mode stars are considered as the energy source of CCRs.

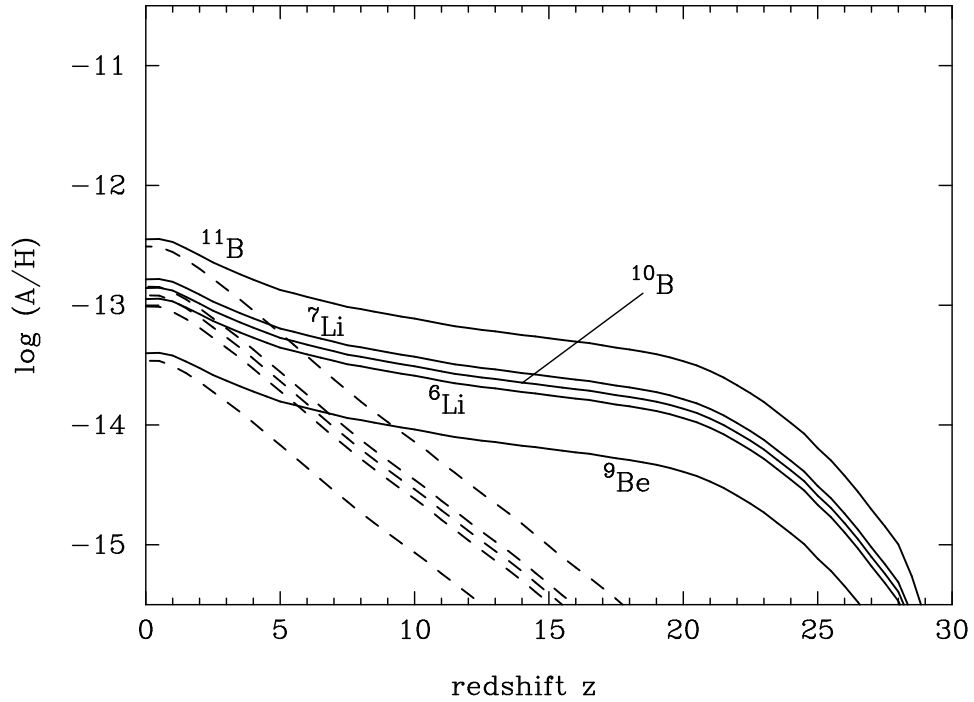


FIG. 8.— Abundances of light elements produced by the secondary process in the ISM as a function of redshift in Model 1 (solid lines).  $\epsilon = 0.31$  is assumed to result in  $^6\text{Li}/H = 6 \times 10^{-12}$  in the IGM at  $z = 3$ . The contribution of the normal mode stars only to the light element production is shown by the dashed lines.

TABLE 1  
ABUNDANCE RESULTS FOR TWO MODELS

Model	$\epsilon$	${}^6\text{Li}/\text{H}$	${}^7\text{Li}/\text{H}$	${}^9\text{Be}/\text{H}$	${}^{10}\text{B}/\text{H}$	${}^{11}\text{B}/\text{H}$
Model 1	0.31	$6.0 \times 10^{-12}$	$7.3 \times 10^{-12}$	$9.0 \times 10^{-14}$	$3.2 \times 10^{-13}$	$7.6 \times 10^{-13}$
Model 1 (Pop II only)	0.73	$6.0 \times 10^{-12}$	$7.3 \times 10^{-12}$	$5.7 \times 10^{-14}$	$2.1 \times 10^{-13}$	$4.9 \times 10^{-13}$
Rapid burst model	0.029	$6.0 \times 10^{-12}$	$7.9 \times 10^{-12}$	$4.4 \times 10^{-13}$	$2.0 \times 10^{-12}$	$5.2 \times 10^{-12}$